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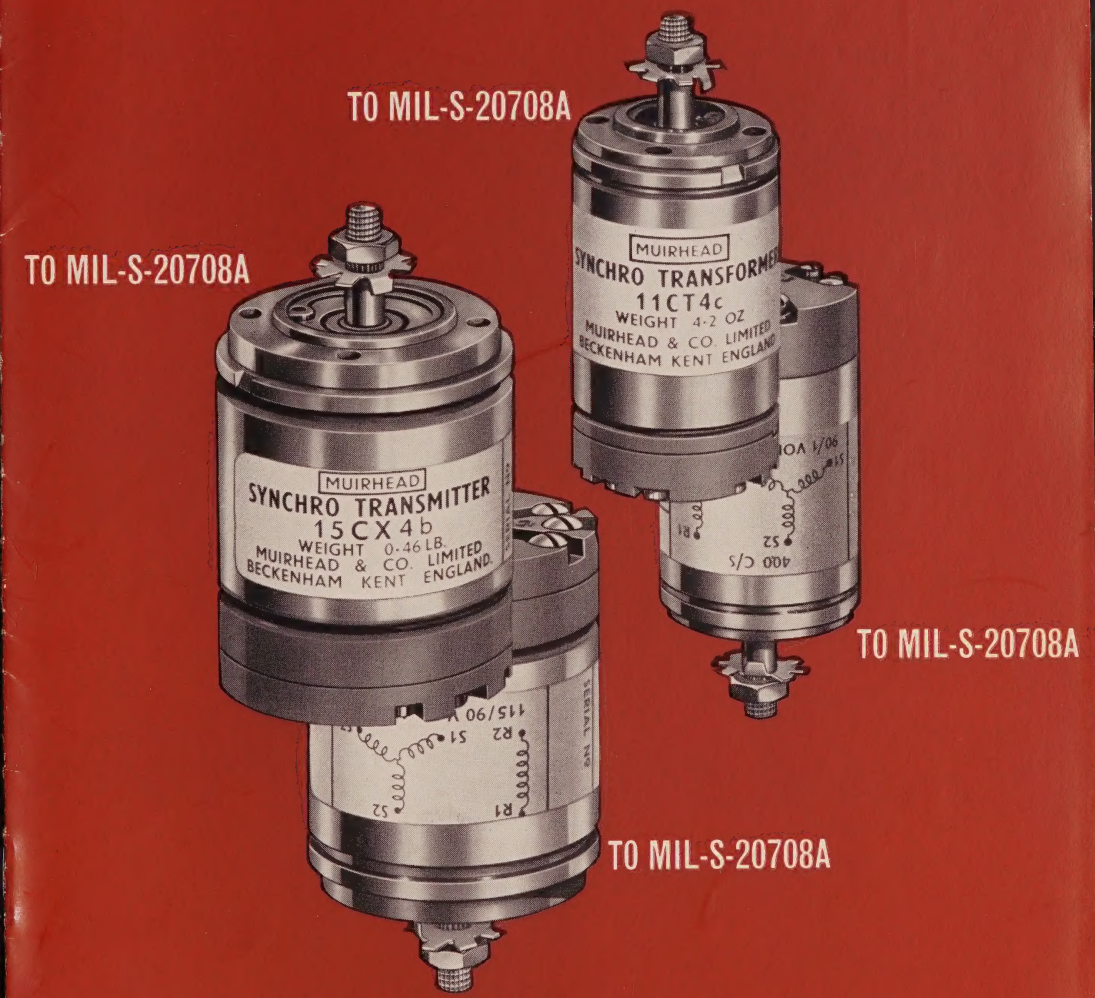
A JOURNAL OF INSTRUMENT ENGINEERING



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THE FRONT COVER

The cover illustration shows two examples from the range of Muirhead Synchros, engineered and manufactured to meet the requirements of the latest United States Department of Defense Specification MIL-S-20708A.

Synchros to this specification, covering 60 c/s and 400 c/s in size 15, and 400 c/s in size 11, are in production and readily available. Other types, conforming to this up-to-date specification, are under development and details will be announced shortly.

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THE INTERPRETATION OF THE FREQUENCY ANALYSIS OF A SIGNAL COMPOSED MAINLY OF SHORT TRANSIENTS, WITH THE D-489 MUIRHEAD-PAMETRADA WAVE ANALYSER

by B. J. Fielding, B.Sc.Tech., A.T.I., A.M.I.Mech.E.*

The frequency analysis of a complex periodic function is used in many forms of investigation and when applied to problems of noise and vibration associated with reciprocating engines it constitutes a powerful experimental tool.[1] In particular the correlation between noise emitted by the surfaces of the prime mover and the movement of the surfaces requires a frequency analysis of the noise generated and of some other variable related to movement over the audible range of frequency. A quantity suitable for measurement which exhibits a fairly constant output over this frequency range and which can be measured relatively easily is acceleration.

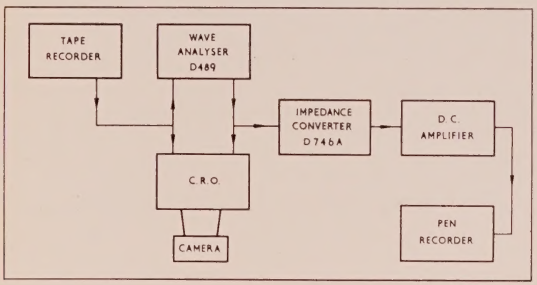

Fig. 1

The signal analysed was the output of a piezo-electric accelerometer mounted on the cylinder head of a two-stroke, three-cylinder, diesel engine which had a fundamental frequency of 15 c/s. A representative length was cut out from the tape recording of the signal and made into a loop which enabled the signal to be played back indefinitely. This signal was fed into the D-489 Muirhead-Pametrada Wave Analyser. Two different tuning conditions were used: in-Tune High (I.T.H.) and Narrow Band (N.B.) and the input and output signals were recorded photographically. A block diagram of the equipment is shown in Fig. 1, and Fig. 2 shows typical oscillograph recordings.†

If a frequency analysis is made in the usual way either by an automatic wave analyser or by the method described in the article appearing on page 22, the meter reading of the wave analyser, when set to damped response, corresponds to the mean height of the rectified output of the wave analyser. Fig. 3 shows the frequency analyses of the signal obtained by the latter method. These results are satisfactory as long as the wave analyser output is reasonably uniform and this varies with the tuning condition. For the particular signal investigated a nearly uniform output signal is obtained only for the range 19–300 c/s (i.e. up to the 20th harmonic) for N.B. tuning and 19–500 c/s (i.e. up to the 34th harmonic) for the I.T.H. condition. At higher frequencies the wave analyser output varies considerably over each cycle due to the input signal containing high-frequency transients of short duration as can be seen in the oscillograms in Fig. 2. Although these transients are periodic in the sense that they are reproduced again in the following cycle their 'Q' is similar to that of the wave analyser, with the result that the 'memory' of the transient is not retained until the end of the cycle, but is lost almost as soon as the transient is passed, and the evidence of its existence is found in the peaks of the output from the analyser.

The waveform under investigation can be divided into three parts:

(i) Below 300 c/s. In this range the harmonics, due to unbalance of the engine and the combustion process, are large. The response of the wave analyser to these harmonics is such that its output is a reasonably uniform sine wave with little modulation.

(ii) 300–900 c/s. This is a transition range where the harmonics of (i) decrease considerably and the short term vibrations, due to impacts whose durations are short in relation to the cycle, become more prominent. The output of the wave analyser becomes less uniform with increasing modulation at the fundamental frequency.

(iii) Above 900 c/s. The character of this vibration is determined mainly by the responses of the structures immediately adjacent to the accelerometer. Short duration high-frequency transients whose response time is similar to that of the wave analyser circuit are superimposed onto the overall vibration. The resulting output is strongly modulated, each transient in the input signal producing a corresponding modulation in the output signal.

The interpretation of the frequency analysis for (i) is straightforward since it can be related directly to the Fourier components at these frequencies but for (ii) and (iii) the relevance of the analysis is obscure. The significance of the analysis at the higher frequencies can be appreciated better if the response of the wave analyser to a square wave is considered.

The theoretical Fourier components of a

*Manchester College of Science & Technology

†See Appendix 2 for details of instrumentation

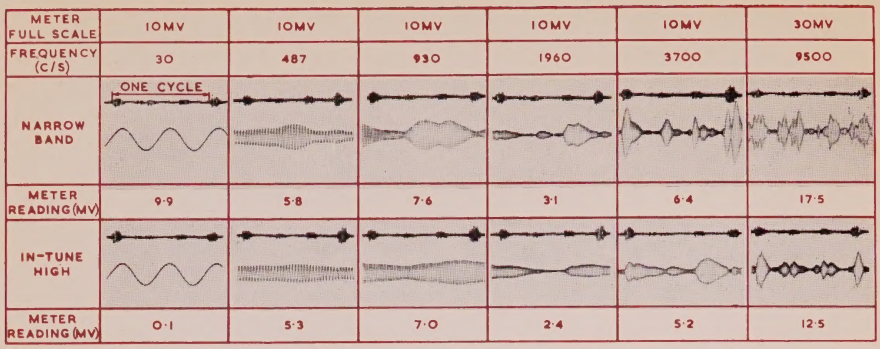

Fig. 2

square wave are easily calculated and afford a basis for the interpretation of the output of the wave analyser. The frequency analyses of a square wave are shown in Fig. 4, and Fig. 5 shows oscillograph recordings of the input and output signals of the wave analyser. The effect of the relation between the periodic time of the 30 c/s square wave, the tuning condition, and the build-up time of the analyser at a particular tuned frequency is evident in the comparison of the output of frequencies up to 930 c/s and those above 3000 c/s. The increasing modulation on the output signal as the tuning frequency is increased, is more exaggerated in the N.B. than the I.T.H. tuning and, due to the wider bandwidth, the N.B. tuning tends to give a higher output over the range 500–1500 c/s since it embraces more than a single harmonic. However, as the frequency exceeds 3000 c/s it is interesting to note that the meter readings at the two tuning conditions become closer and yet the ratio of the maximum amplitudes of the output signals is increasing and is of the order of 2:1. The amplitudes of the 'harmonics' (the meter readings) at high frequencies are dependent upon the modulation imposed by the analyser circuit, consequently, these values cannot be considered as Fourier components as understood in the normal mathematical sense.

The response of two tuned amplifiers in cascade to simple transients have been mathematically analysed[2,3] but the analysis of the response to a transient of the type occurring in the original signal would be impractical due to

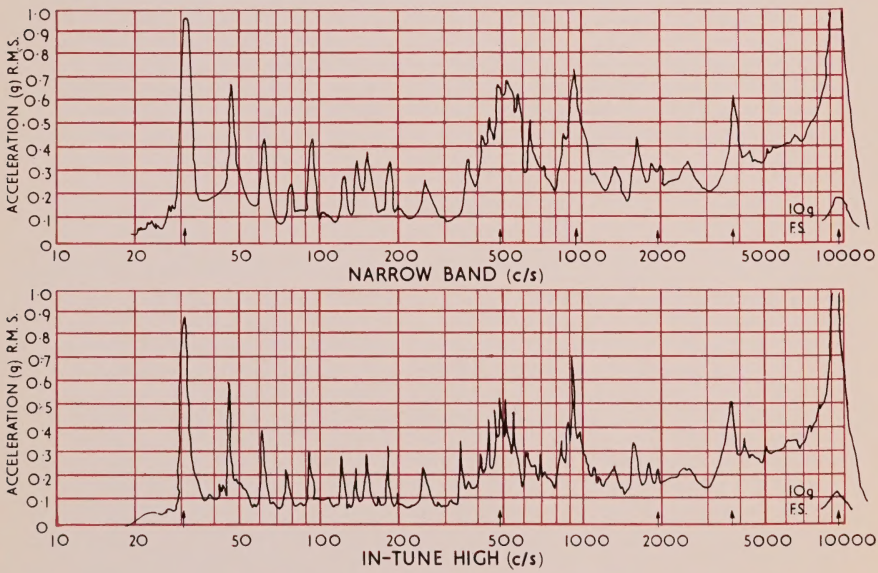

Fig. 3

its complexity. The transients occurring in the original signal can be represented by the summation of damped sinusoidal terms:

$$x = \Sigma A_n e^{-\alpha_n t} \sin(\omega_n t + \phi_n) \text{ for } t > 0$$

The final form of the transient in the output signal will be a combination of the original decaying transient and the modulation introduced by the wave analyser. In order to separate these two effects it has been suggested[4,5] that the signal should be reversed by reversing the direction of replay of the tape which would then produce a transient of the form:

$$R = -\Sigma A_n e^{\alpha_n t} \sin(\omega_n t - \phi_n) \text{ for } t < 0$$

This signal when fed into the analyser would result in an output whose rate of build-up is independent of the analyser circuit. This means that α_n hence the Q can be determined for the original transient. The maximum amplitude of the output transient is also shown to be related to the maximum amplitude of the original transient but extensive tests would be required before any confidence could be placed in the value of amplitudes determined by this technique.

To summarise, the choice of tuning condition for the kind of signal described here should to some extent depend upon the frequency range which is of interest. In the lowest range, say up to 200 c/s, where the individual harmonics are distinct and spaced sufficiently far apart, the N.B. may be used with advantage since the higher selectivity of I.T.H. requires the use of

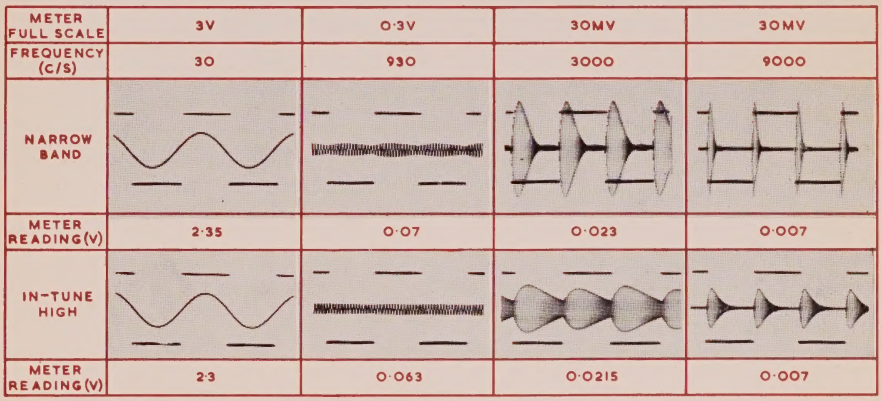

Fig. 4

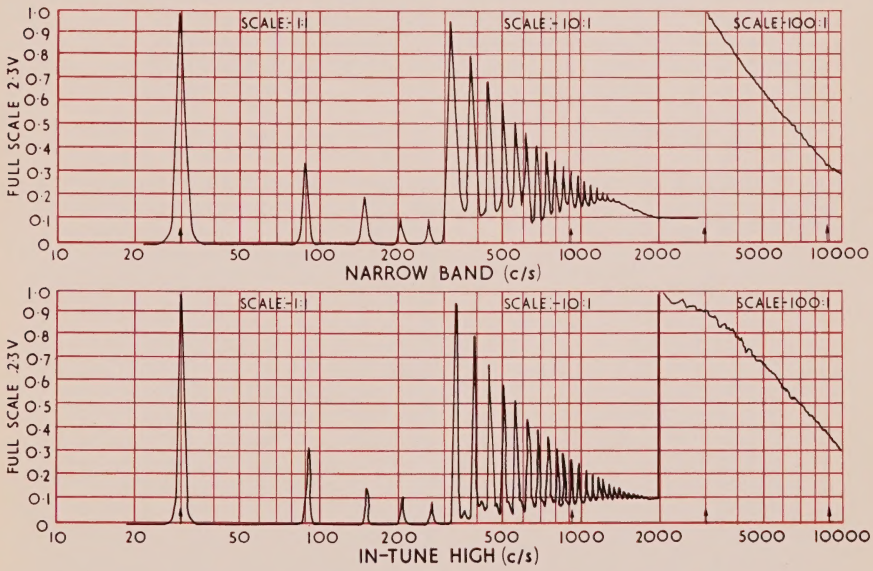

Fig. 5

the Fine Selectivity control if the full amplitude of the harmonics is to be realised. Above 200 c/s the higher selectivity of I.T.H. can be used to advantage to identify individual harmonics without the necessity of using the Fine Selectivity control. In addition, the output of the analyser tends to be more uniform for I.T.H. hence it more closely approximates to the concept of a Fourier component. However, there is a limiting frequency, about 2 kc/s, above which identification of individual harmonics is no longer possible and the output of the analyser becomes heavily modulated whether tuned to I.T.H. or N.B., the resulting spectra from the two tuning conditions being very similar. The meter reading which is now recorded on the frequency spectrum corresponds only to the mean value of the rectified output of the wave analyser and no longer has any relevance as a Fourier component. However, where comparative results of similar signals are required, the 'harmonics' above 2 kc/s are useful, but for detailed interpretation, the oscillograms of the output signal should be studied.

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APPENDIX 1

Notation

x Output of tape recorder when played back direct.

R Output of tape recorder when played back reversed.

A_n Initial amplitude of the nth mode of vibration.

ω_n Circular frequency of the nth mode of vibration.

ϕ_n Phase angle of the nth mode of vibration.

α_n Logarithmic decrement of the nth mode of vibration.

t Time.

APPENDIX 2

Instruments

D-489 MUIRHEAD-PAMETRADA WAVE ANALYSER

This instrument has a constant percentage bandwidth which means that for any particular tuning condition it has a constant Q. The time constant for the circuit (i.e. the time required for the output to reach 96% of the input signal) is given by Q/f where f is the tune frequency in c/s. A more convenient way of expressing this is to say the output from the analyser will attain the true maximum value after Q cycles independently of the frequency.

For the two tuning conditions used:

In-Tune High Q = 80

Narrow Band Q = 24

Other Instruments

The oscillograms were obtained by photographing the traces of a double-beam cathode ray oscilloscope having a rise time of 2 microseconds.

The square wave signal was derived from a double-pulse generator having a rise time of about two millimicro-seconds.

A SEMI-AUTOMATIC TECHNIQUE OF WAVEFORM ANALYSIS

by J. Skorecki, M.Sc.Tech., B.Sc.(Eng.), Ph.D., A.M.I.Mech.E.*

Muirhead-Pametrada Wave Analysers have been used to obtain large numbers of spectra of vibration, sound and pressure waveforms by employing a semi-automatic technique which relies on simultaneous manual operation of two instruments: a wave analyser and a pen recorder. The latter instrument is an adaptation of an Eversheds and Vignoles Single Channel Recording Milliameter.

The signals to be analysed are either fed into

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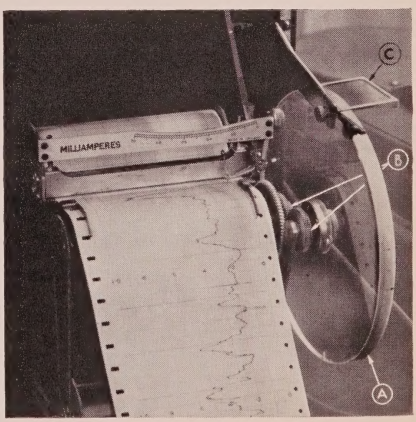

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THE USE OF A WAVE ANALYSER IN HALL-EFFECT SYNCHRO INVESTIGATIONS

by G. W. Donaldson, M.A., B.Sc.(Oxon), B.E.*

Synchro transmitters are required to have phase voltages as close as possible to sine functions of rotor position. The investigation of small harmonic errors in these voltages presents a problem. By using a suitable wave analyser and the method set out below, such an investigation can be carried out.

In Hall-effect synchro transmitters, which do not have inductively coupled windings like normal synchros, no rate of change of flux linkage is involved. It is therefore permissible and convenient to turn the rotor at constant speed. The output voltages are then functions of time instead of position or angle and consequently, more suitable for analysis or display than voltages related to a stationary position would be.

The Hall-effect voltage generated in an element carrying a current i in a magnetic field of mean flux density b is proportional to the instantaneous product of i and b. Let the Hall element be excited with 400 c/s current, and let the flux be produced by a 2-pole rotor turned at 2400 r.p.m.

$$i = \mathrm{I} \sin(\omega_e t + \phi_e), \text{ where } \omega_e = 2\pi 400$$

$$b = \mathrm{B}_1 \sin(\omega_1 t + \phi_1), \text{ where } \omega_1 = 2\pi 40$$

The Hall voltage v is given by:

$$\begin{aligned} v &= \mathrm{KiB} \\ &= \mathrm{KIB}_1 \sin(\omega_e t + \phi_e) \sin(\omega_1 t + \phi_1) \\ &= \mathrm{KIB}_1/2 \left[\cos\{(\omega_e - \omega_1)t + (\phi_e - \phi_1)\} \right. \\ &\qquad \left. - \cos\{(\omega_e + \omega_1)t + (\phi_e + \phi_1)\} \right] \end{aligned}$$

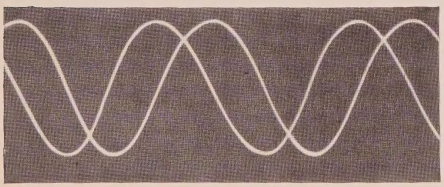

Fig. 2. Two-phase Hall voltages, d.c. excitation.

A wave analyser would measure two voltages of equal magnitude and of side-band frequencies $(\omega_e - \omega_1)$ and $(\omega_e + \omega_1)$, the carrier frequency having disappeared.

Should the mean flux density across the Hall element not be a pure sine function of time, but contain harmonics, it may be written as:

$$b = \mathrm{B}_1 \sin(\omega_1 t + \phi_1) + \mathrm{B}_2 \sin(2\omega_1 t + \phi_2) + \cdots\cdots$$

The Hall voltage $v = \mathrm{Kib}$ would then appear as:

$$\begin{aligned} v = \mathrm{KIB}_1/2 \left[\cos\{(\omega_e - \omega_1)t + (\phi_e - \phi_1)\} \right. \\ \left. - \cos\{(\omega_e + \omega_1)t + (\phi_e + \phi_1)\} \right] \\ + \mathrm{KIB}_2/2 \left[\cos\{(\omega_e - 2\omega_1)t + (\phi_e - \phi_2)\} \right. \\ \left. - \cos\{(\omega_e + 2\omega_1)t + (\phi_e - \phi_2)\} \right] \\ + \mathrm{KIB}_3/3, \text{ etc.} \end{aligned}$$

With a 400 c/s carrier and a 40 c/s fundamental modulation, a wave analyser should, therefore, measure two equal components at 360 and 440 c/s proportional to the magnitude B, of the fundamental of the flux wave, two equal components at 320 and 480 c/s proportional to the magnitude B_2 of the second harmonic, etc. The second harmonic is thus measured at a frequency which is only about 10% away from the fundamental. Also it is only about 1% of the fundamental in magnitude. The D-489 Muirhead-Pametrada Wave Analyser is a suitable instrument to use, particularly when adjusted for increased selectivity. At 10% off tune the attenuation is then 50dB, and the unwanted signal is therefore reduced to 0·3% of its amplitude.

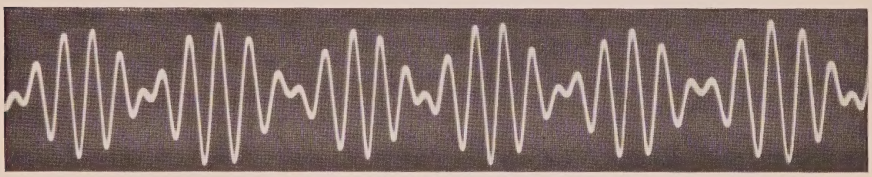

Fig. 1. One-phase Hall voltage, 400 c/s excitation.

In addition to the side-band frequencies resulting from the fundamental and harmonics of the flux density b, there is always a reading at carrier frequency. It is due to the standing voltage which appears in the output of every Hall element. This voltage is independent of flux and may be treated as a resistance drop proportional to the exciting current. It therefore appears at carrier frequency. The equation for the Hall voltage becomes $v = Kib + ir$. This resistance drop is always in phase with the exciting current, whereas the Hall voltage is

*Servo Laboratory, Muirhead & Co., Limited on leave from The University of New South Wales.

either in phase or 180° out. It adds to the Hall voltage for one-half cycle of the fundamental of the modulating frequency and subtracts from the other half-cycle. Hence groups of waves vary slightly in amplitude, as seen in Fig. 1.

The analysis of the voltage in Fig. 1 is shown in Table 1.

If d.c. excitation is used instead of a.c. the analysis of the Hall voltage is simplified, but the test is one step further removed from operating conditions. If the flux-producing rotor is again rotated at 2400 r.p.m., the resulting Hall voltage will contain a 40 c/s fundamental and harmonics which are simple multiples of 40 c/s. They are, therefore, easier to separate from the fundamental than in the case of a.c. excitation given above. The standing voltage is d.c. and does not effect the measurement of harmonics. Fig. 2 shows an oscillogram of typical voltages produced by d.c. excitation of two phases of an experimental Hall synchro. Table 2 shows the analysis of one-phase voltage.

TABLE 1

	Carrier	*Fundamental*	*Harmonic* c/s					
			2nd	3rd	4th	5th	6th	7th
Frequency (c/s)	400	440	480	520	560	600	640	680
		360	320	280	240	200	160	120
Voltage (mV)	23·5	130	4·75	1·1	0·1	0·2	0·18	0·1
		130	4·60	1·0	0·1	0·2	0·16	0·1
Average Harmonics %	—	100	3·6	0·8	0·1	0·2	0·1	0·1

TABLE 2

Harmonic	1	2	3	4	5	6	7	8	9
% Fundamental	100	2·2	1·7	0·1	0·4	—	0·1	—	—

Continued from page 22

the wave analyser directly from a transducer or, as in the majority of cases, recorded on magnetic tape and later replayed from a loop. The length of loops used is 22½ inches and the tape speed, both recording and replaying, is 15 in./sec. The output of the wave analyser is fed into the pen recorder via a Muirhead D-746-A Impedance Converter set to d.c., and a d.c. amplifier.

The main features of the adaptation of the pen recorder are shown in the illustration. The recorder chart is advanced by turning the wheel A. Gears B reduce the speed of the wheel in the ratio of 9:8 in order to give a more convenient feed of chart of 4 inches for one revolution. The wheel has on its periphery a logarithmic frequency scale covering one decade and is advanced in step with the frequency selecting control of the wave analyser.

In the actual operation the wave analyser and the pen recorder are placed near each other so that the operator can conveniently select the frequency in the wave analyser with his left hand while he uses his right hand to advance the recorder wheel and his eyes to check its position against a hairline on the cursor C.

The average time taken to obtain a three-decade Narrow Band spectrum is 20 minutes. An additional operation of transferring the record from the standard chart to a special graph paper on a copying table takes about 5 minutes.

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